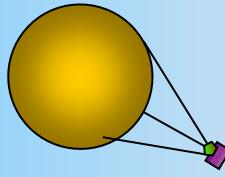


# Analysis of Temperature-Constrained Ballute Aerocapture for High-Mass Mars Payloads

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*Alina A. Alexeenko<sup>(2)</sup>*

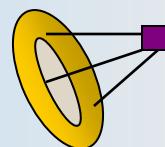
*James M. Longuski<sup>(3)</sup>*



6<sup>th</sup> International Planetary Probe Workshop

Atlanta, Georgia

June 23-27, 2008



<sup>(1)</sup> Graduate Student, Purdue University

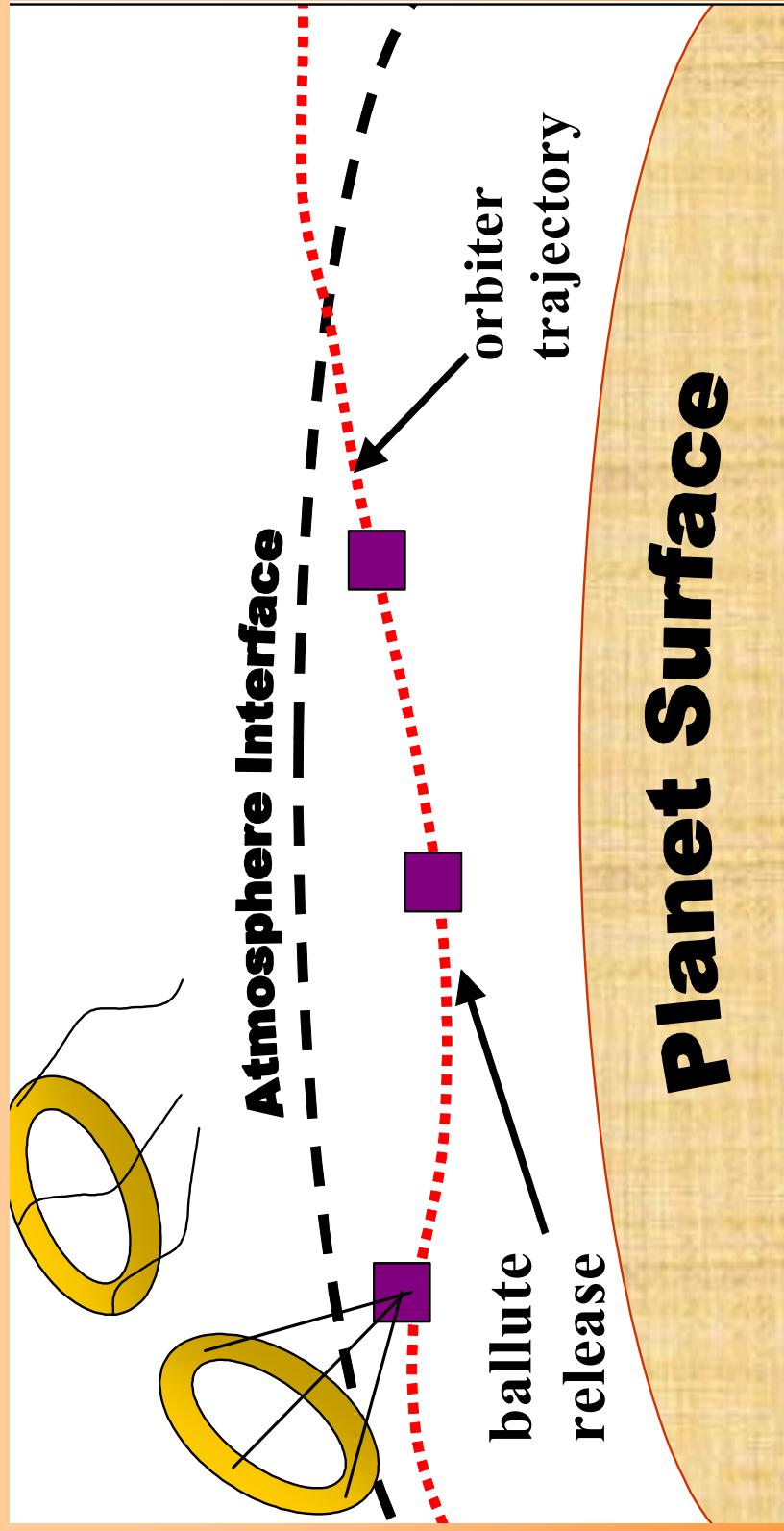
<sup>(2)</sup> Assistant Professor, Purdue University

<sup>(3)</sup> Professor, Purdue University

Funded in part by NASA GSRP Fellowship through MSFC

MSFC Technical Advisor: Bonnie F. James

# *Can towed ballutes be used to capture high mass systems at Mars?*



High-fidelity aerothermodynamic analysis must be achieved



# Temperature-Constrained Trajectories

for Towed Toroidal Ballute Aerocapture at Mars

**Ballute Surface Temperature  $\leq 500^{\circ}\text{C}$**   
*(equivalent to  $Q_s = 2.01 \text{ W/cm}^2$ )*

**Hyperersonic Planetary  
Aeroassist Simulation System  
(HyperPASS)**

Simulation Parameters

- Vehicle Mass: 0.1, 1, 10, and 100 tons (sans ballute)
- Entry Speed = 6.0 km/s (at 150km)
- Target: 4-day Mars parking orbit
- $C_{D,ball}$  = 2.00 (varies with Kn)
- $C_{D,s/c}$  = 0.93 (constant)
- 3DOF trajectory simulations
- point-mass vehicle representation
- variable  $C_D$  model
- rotating atmosphere (with planet)
- Exponentially interpolated atmosphere (Mars COSPAR90)

# Ballute Sizing Results

for Temperature-Constrained Ballute Aerocapture at Mars

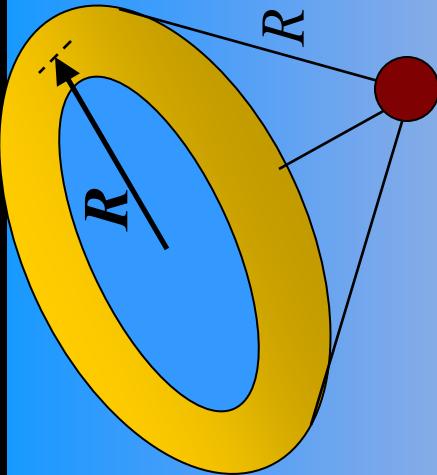


Ballistic Coefficient

$$\beta = \frac{m_{s/c} + m_{ball}}{C_{D,s/c} A_{s/c} + C_{D,ballute} A_{ball}}$$

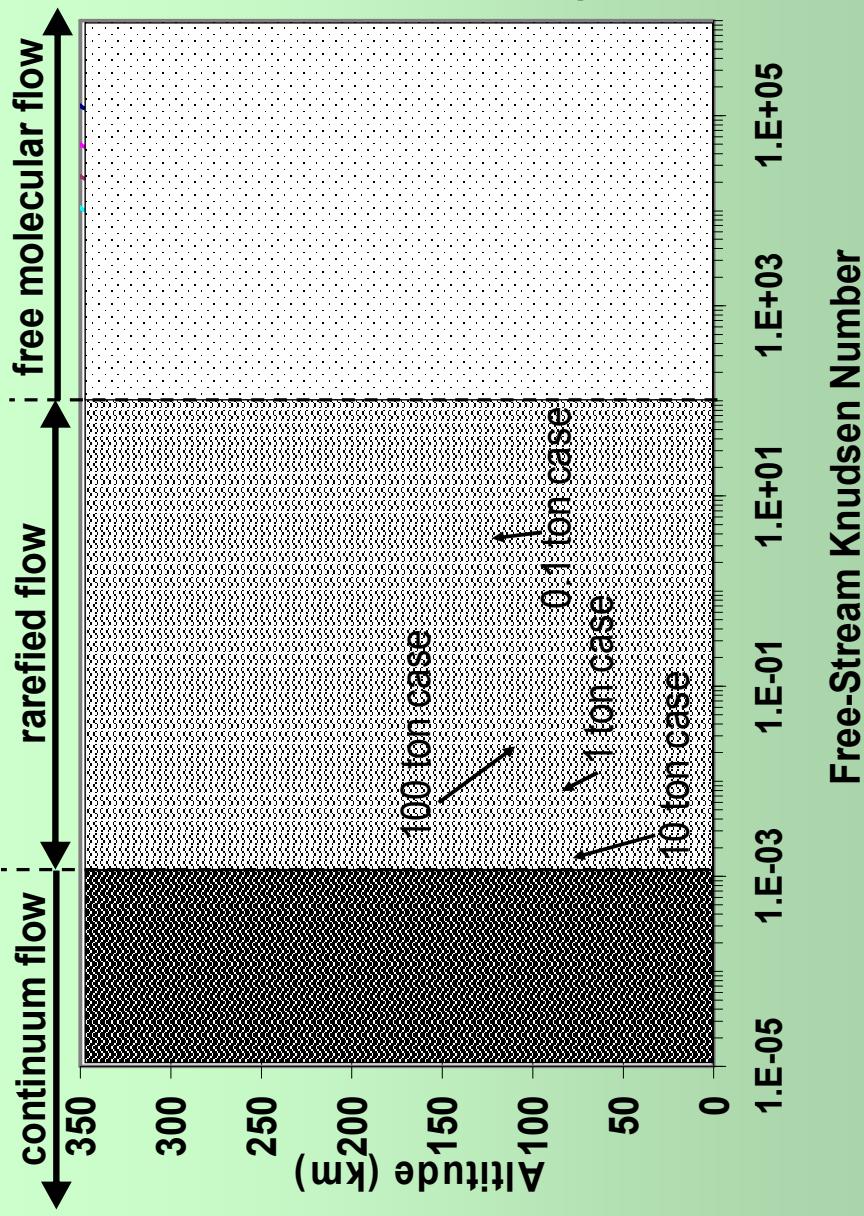
$$r_{ball} = R/4$$

$$R \left[ \beta, C_{D,ball}, C_{D,s/c}, A_{s/c}, m_{s/c}, \sigma \right]$$



Parameter	0.1 ton case			1 ton case			10 ton case			100 ton case		
	s/c	ballute	s/c	ballute	s/c	ballute	s/c	ballute	s/c	ballute	s/c	ballute
<b><i>m</i> [kg]</b>	<b>100</b>	<b>3.20</b>	<b>1000</b>	<b>20.9</b>	<b>10,000</b>	<b>98.2</b>	<b>100,000</b>	<b>100</b>	<b>100,000</b>	<b>1000</b>	<b>100,000</b>	<b>453</b>
<b><i>A</i> [m<sup>2</sup>]</b>	<b>2.00</b>	<b>103</b>	<b>5.64</b>	<b>669</b>	<b>26.1</b>	<b>3140</b>	<b>121</b>	<b>14500</b>				
<b><i>r</i> [m]</b>	<b>0.80</b>	<b>1.43</b>	<b>1.34</b>	<b>3.66</b>	<b>2.88</b>	<b>7.91</b>	<b>6.20</b>	<b>17.0</b>				
<b><i>R</i> [m]</b>	---	5.73	--	14.59	--	31.63	--	67.94				
<b><i>Initial β</i> [kg/m<sup>2</sup>]</b>	<b>0.50</b>		<b>0.76</b>		<b>1.60</b>		<b>3.45</b>					

# Altitude vs. Knudsen Number



$Kn = \frac{\lambda}{L}$

$Kn > 100$ : free molecular flow  
 $Kn < 10^{-3}$  : continuum flow  
in between is rarefied and transitional flow

# Flow Conditions

at Point of Maximum Heat Flux



Indicates laminar vs. turbulent flow

Indicates rarefied vs. continuum flow regime

CASE	Ballistic Coeff. [kg/m <sup>2</sup> ]	Char. Length [m]	Altitude @ max heating [km]	Knudsen Number	Reynolds Number
0.1 ton case	0.50	2.86	90.99	2.63x10 <sup>-2</sup>	878
1 ton case	0.76	7.31	87.15	6.20x10 <sup>-3</sup>	3745
10 ton case	1.60	15.82	81.40	1.30x10 <sup>-3</sup>	17497
100 ton case	3.45	33.98	75.64	3.00x10 <sup>-4</sup>	81398

← rarefied,  
laminar flow

continuum,  
turbulent flow

# Aerothermodynamic Tools



## DSMC

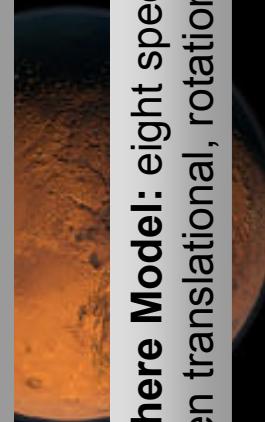
### Statistical Modeling In Low-density Environment (SMILE)

- 3D/2D/axisymmetric code
- 3 million simulated molecules
- constant wall temperature assumed
- gas-surface interactions assumed to be diffuse, with full energy accommodation
- variable-hard-sphere molecular model

## CFD

### Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA)

- 3D/2D/axisymmetric code
- grid resolution, ~27500 cells
- radiative equilibrium wall temperature
- super-catalytic wall boundary
- governing equations: Full Navier-Stokes
- laminar flow assumed

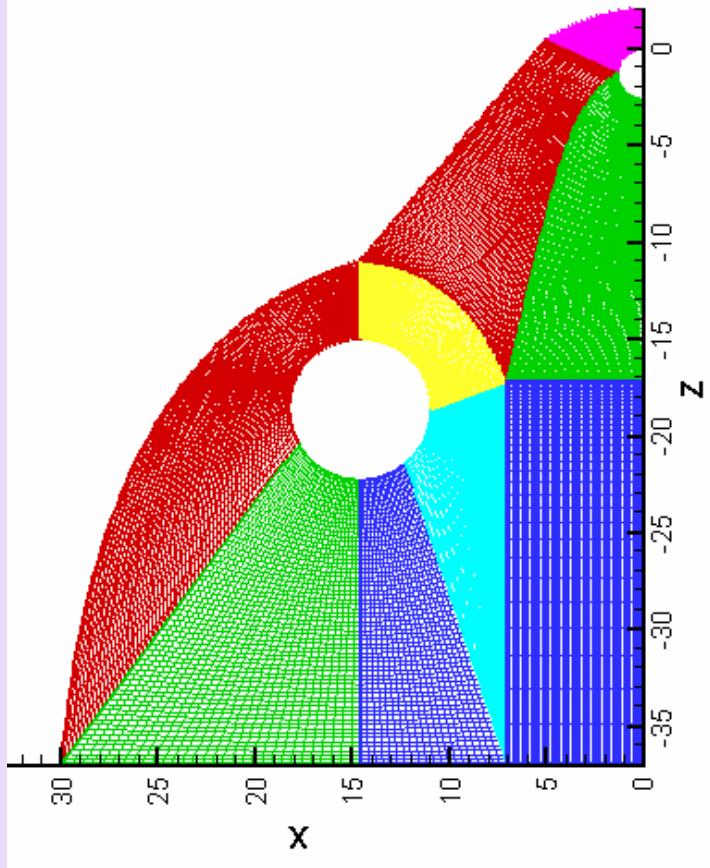


**Martian Atmosphere Model:** eight species gas model with chemical reactions and exchange between translational, rotational, and vibrational modes.

# CFD Numerical Issues



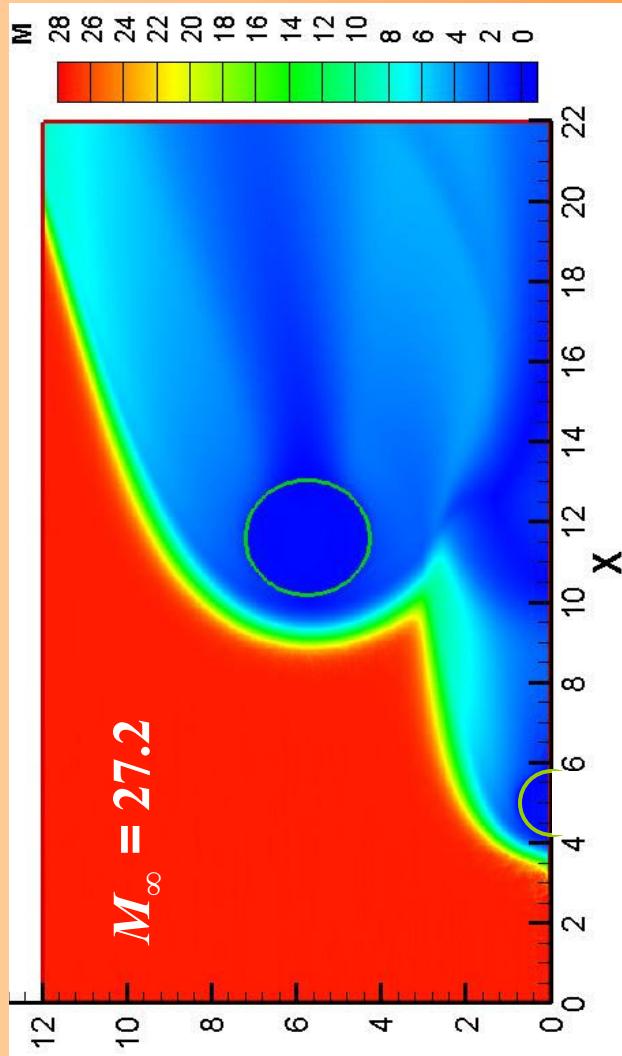
- 9 blocks, 27500 cells
- grid not fully converged
- cell Reynolds number
  - minimum cell  $Re = 0.03$
  - maximum cell  $Re = 13.06$
- Convergence residual
  - minimum residual =  $10^{-5}$
  - maximum residual =  $10^{-3}$



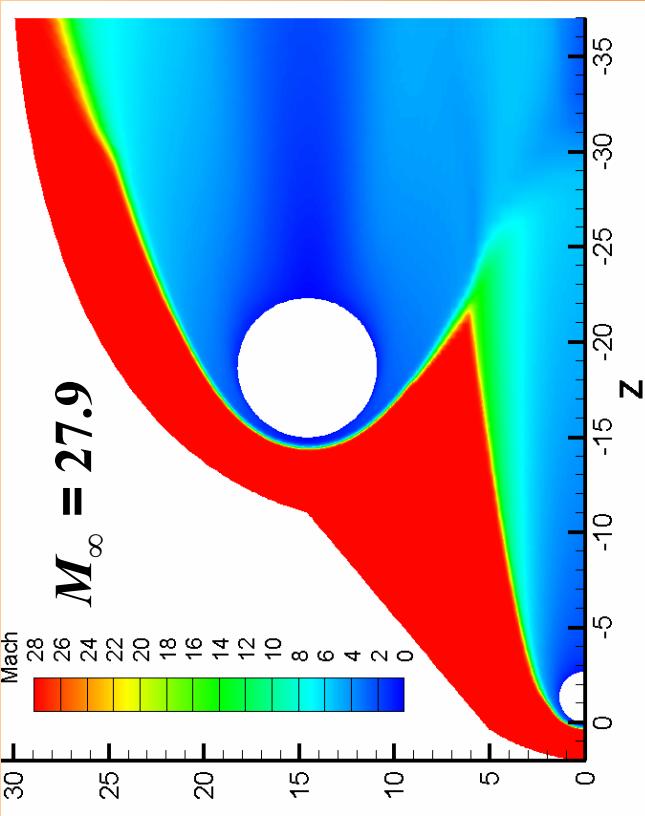
# Mach Number



**0.1 ton payload,  $\beta = 0.50$  (DSMC results)**  
 $Kn = 2.63E-2$ ,  $V_\infty = 5.38$  km/s



**1 ton payload,  $\beta = 0.76$  (CFD results)**  
 $Kn = 6.20E-3$ ,  $V_\infty = 5.39$  km/s



Complex hypersonic flow, combining normal and oblique shock waves around the spacecraft and ballute.

# 0.1 ton Pressure & $C_D$ (DSMC)

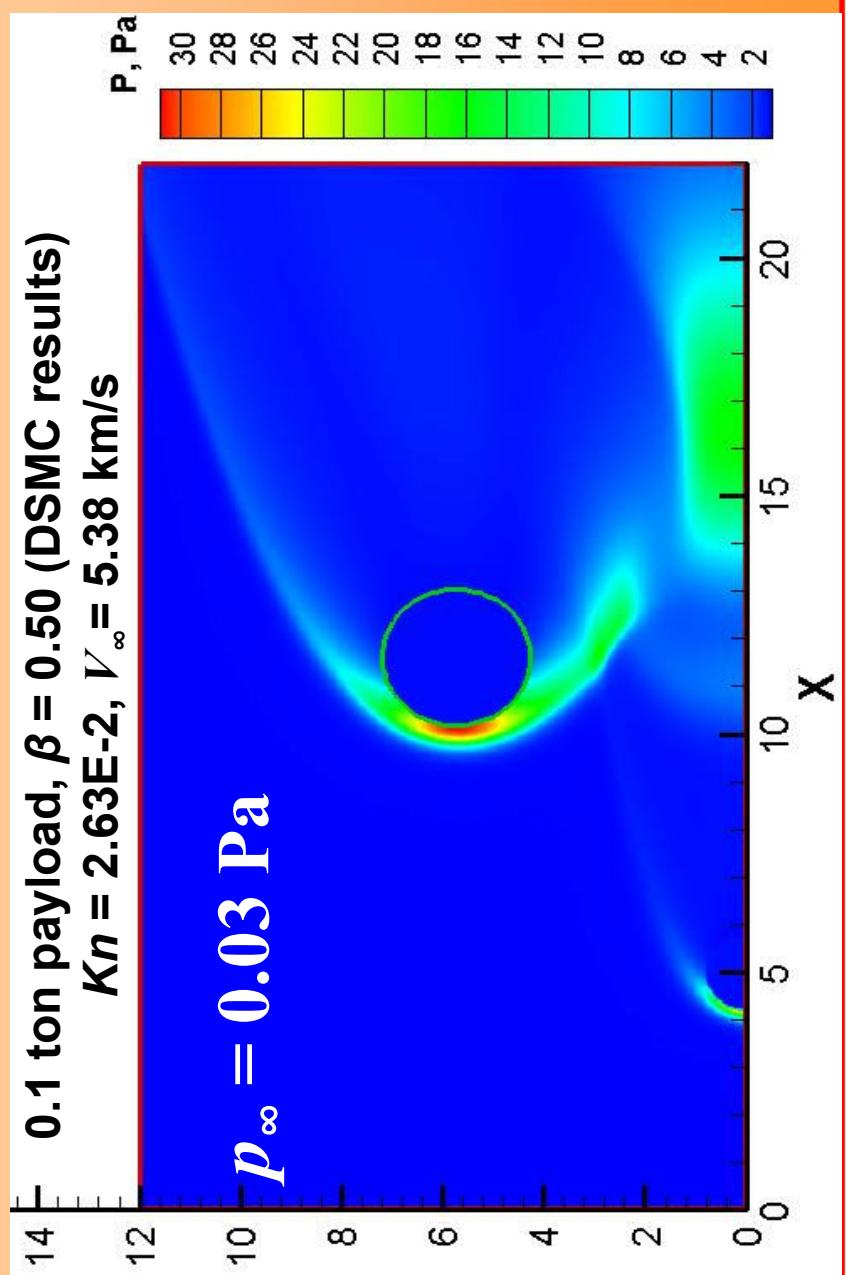


$$C_D = \frac{2D}{\rho V^2 A}$$

$\longleftrightarrow$  Sum of surface pressure and friction forces in the x-direction

$$P_\infty = 0.03 \text{ Pa}$$

Based on Moss' DSMC calculations for air:  
 $C_D = 1.32$

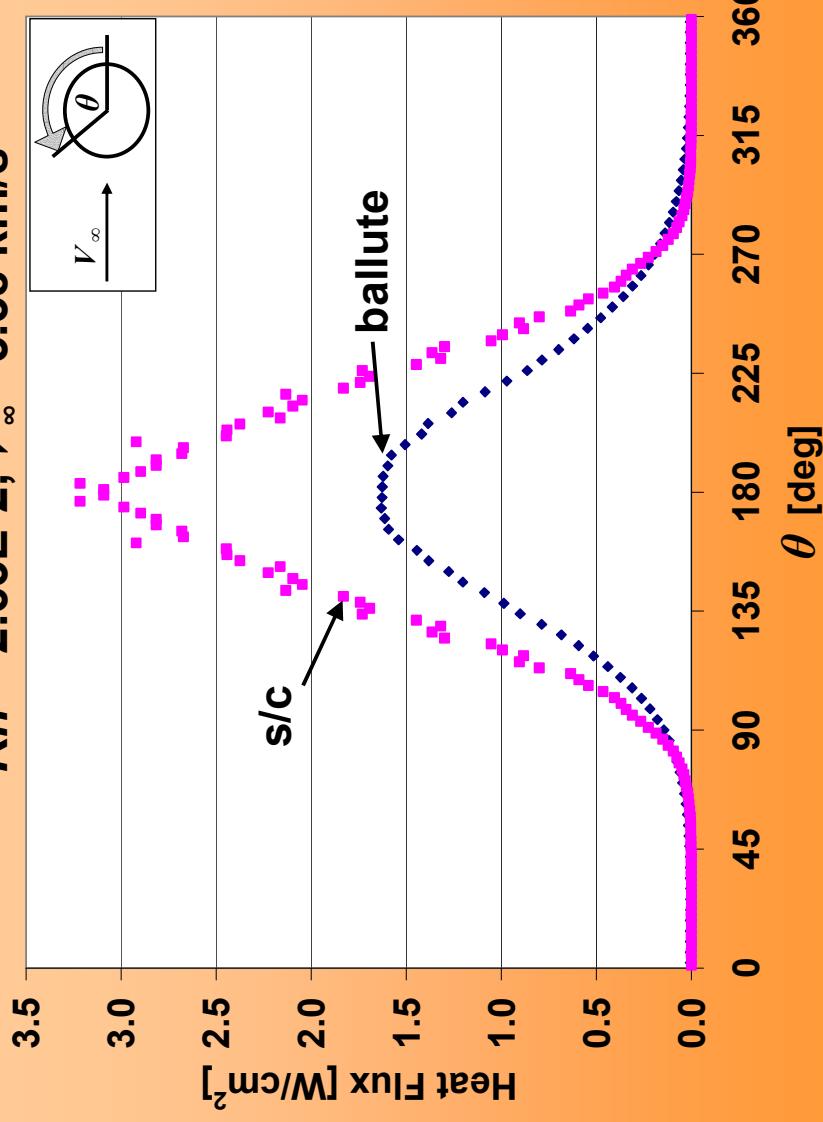
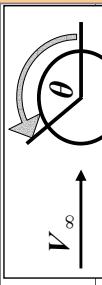


DSMC results for Mars:  
 $C_D = 1.48$   
 (12% higher)

# 0.1 ton Surface Heating (DSMC)



0.1 ton payload,  $\beta = 0.50$  (DSMC results)  
 $Kn = 2.63E-2$ ,  $V_\infty = 5.38$  km/s



$$Q_{stag} = C_V^3 \sqrt{\frac{\rho}{R_n}} \downarrow$$

Sutton-Graves model :

assuming  $C = 2.62 \times 10^{-8}$  kg<sup>1/2</sup>/m

$$Q_s = 2.47 \text{ W/cm}^2 \text{ ballute}$$

$$Q_s = 3.31 \text{ W/cm}^2 \text{ orbiter}$$

DSMC results:

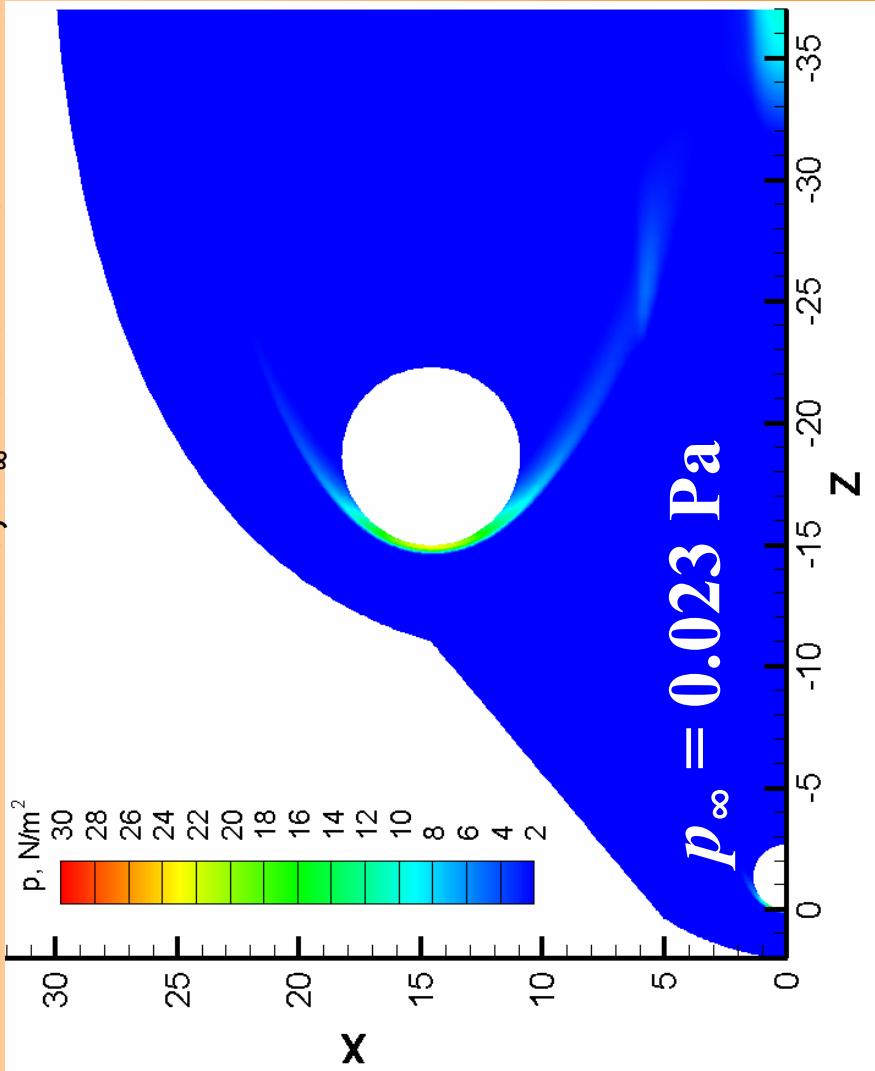
$$Q_s = 1.63 \text{ W/cm}^2 \text{ ballute} \\ (34\% \text{ lower})$$

$$Q_s = 3.09 \text{ W/cm}^2 \text{ orbiter} \\ (6\% \text{ lower})$$

# 1 ton Pressure & $C_D$ (CFD)



1 ton payload,  $\beta = 0.76$  (CFD results)  
 $Kn = 6.20E-3$ ,  $V_\infty = 5.39$  km/s



Based on Moss'  
DSMC calculations  
for air:

$$C_D = 1.32$$

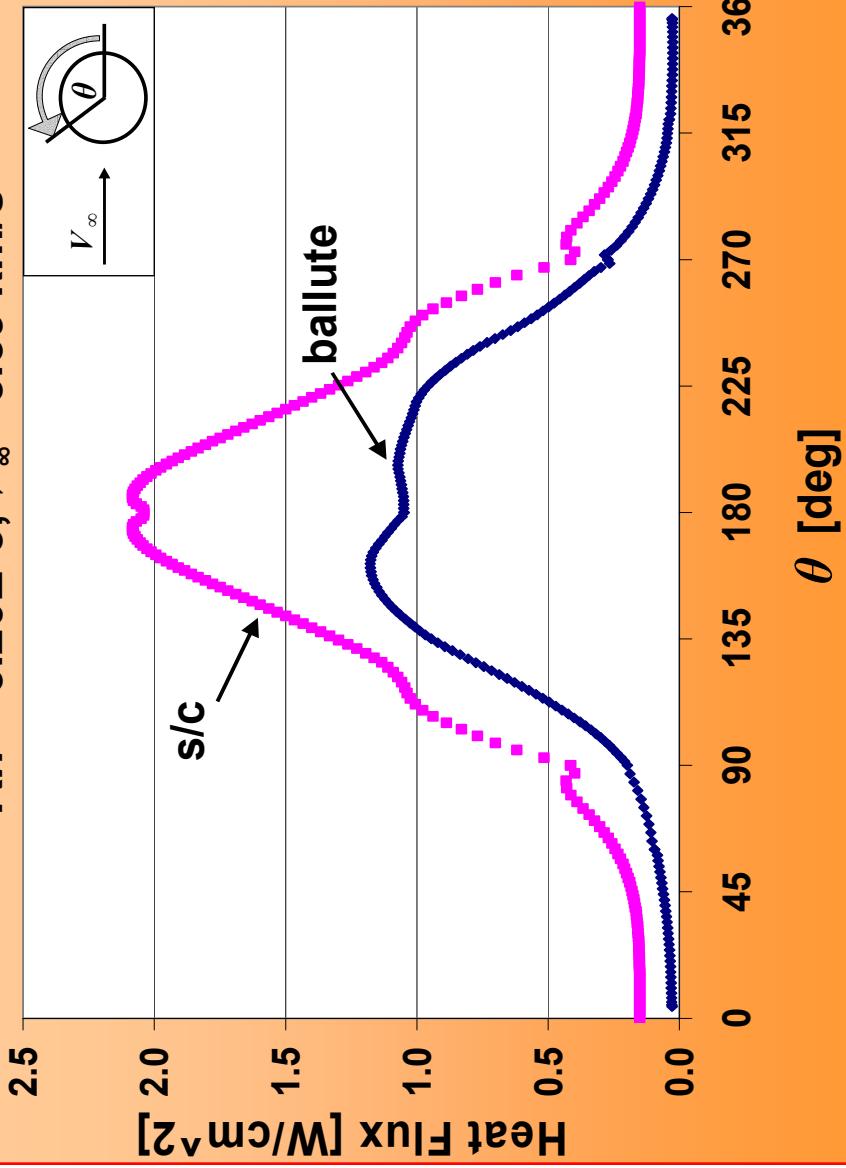
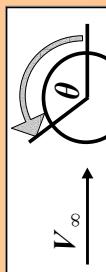
Preliminary CFD  
results for Mars:  
 $C_D = 1.52$   
(expected to be lower  
when fully converged)

# 1 ton Surface Heating (CFD)



1 ton payload,  $\beta = 0.76$  (CFD results)

$$Kn = 6.20E-3, V_\infty = 5.39 \text{ km/s}$$



$$Q_{stag} = C_V^3 \sqrt{\frac{\rho}{R_n}}$$

Sutton-Graves model :

assuming  $C = 2.62E-8 \text{ kg}^{1/2}/\text{m}$

$$Q_s = 2.01 \text{ W/cm}^2 \text{ ballute}$$

$$Q_s = 3.32 \text{ W/cm}^2 \text{ orbiter}$$

Preliminary CFD results:

$$Q_s = 1.18 \text{ W/cm}^2 \text{ ballute} \\ (41\% \text{ lower})$$

$$Q_s = 2.08 \text{ W/cm}^2 \text{ orbiter} \\ (37\% \text{ lower})$$

# Conclusions



- Aerothermodynamic analysis indicates that  $C_D$  for Mars is higher than the  $C_D$  calculated for air at the same Knudsen number (as expected).
- Aerothermodynamic analysis (both DSMC and preliminary CFD) predict a lower ballute heat flux than estimated by Sutton-Graves model (34 % lower for the 0.1 ton case and 41 % lower for the 1 ton case).
- Heating results suggest that ballute-spacecraft systems with larger ballistic coefficients (than predicted by the Sutton-Graves model) are feasible for Mars aerocapture.

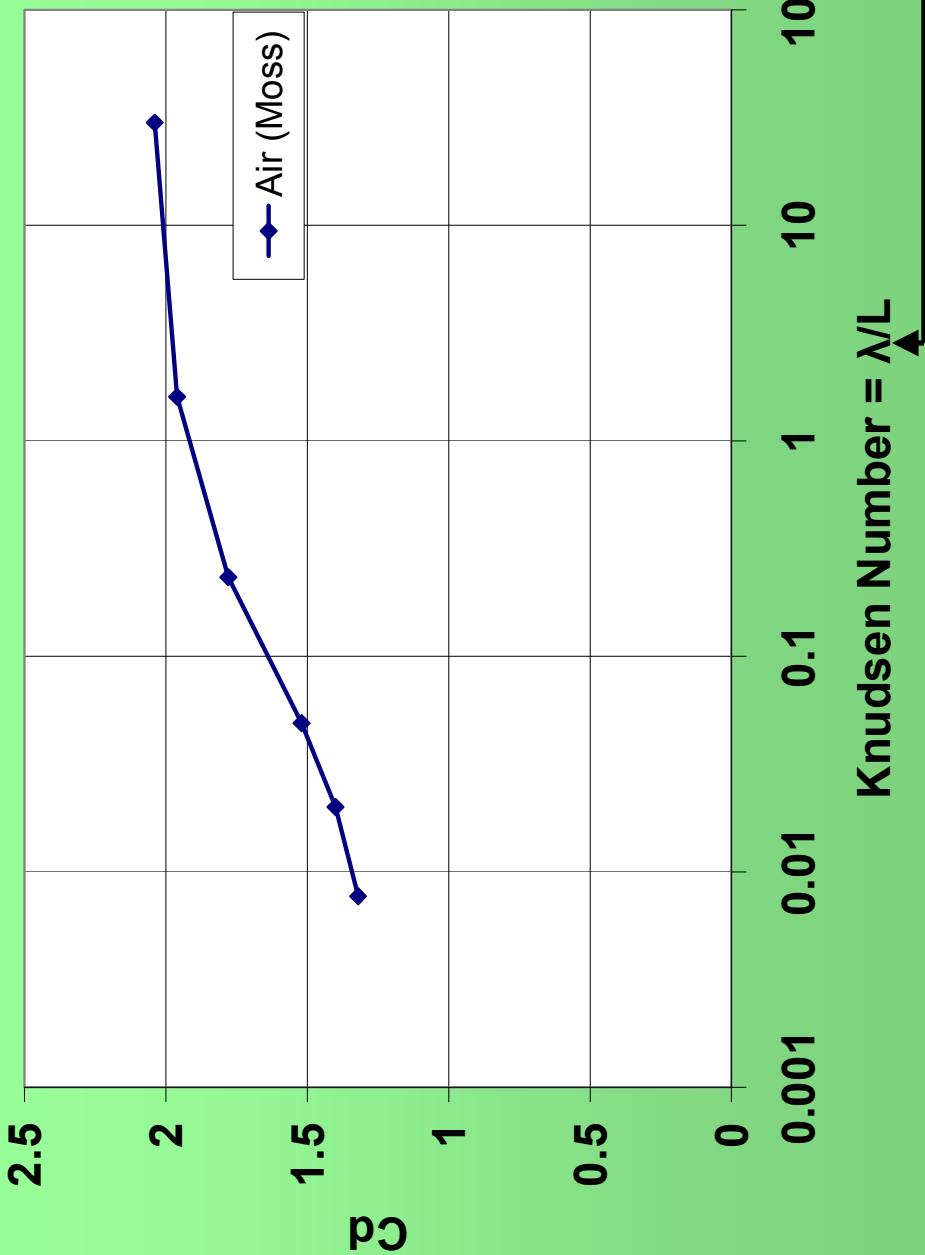


# Back-up Slides

June 25, 2008

Medlock, Alexeenko, Longuski

# DSMC Predictions for $C_D$ vs. Kn (Earth)

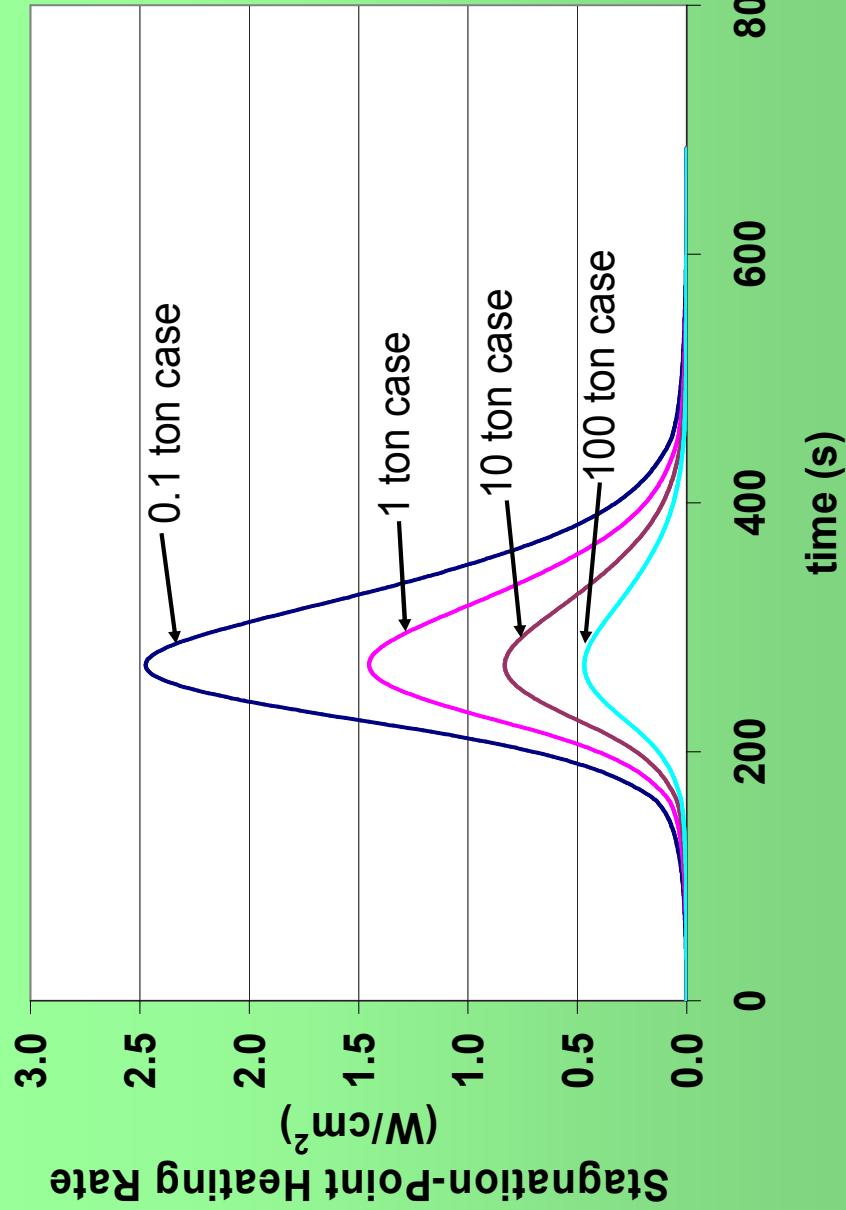


Moss, “*DSMC Simulations of Ballute Aerothermodynamics Under Hypersonic Rarefied Conditions*”, AIAA 2005-4949.

$$D = \frac{1}{2} \rho V^2 A C_D$$

function of Kn

# Stagnation Point Heating Rate



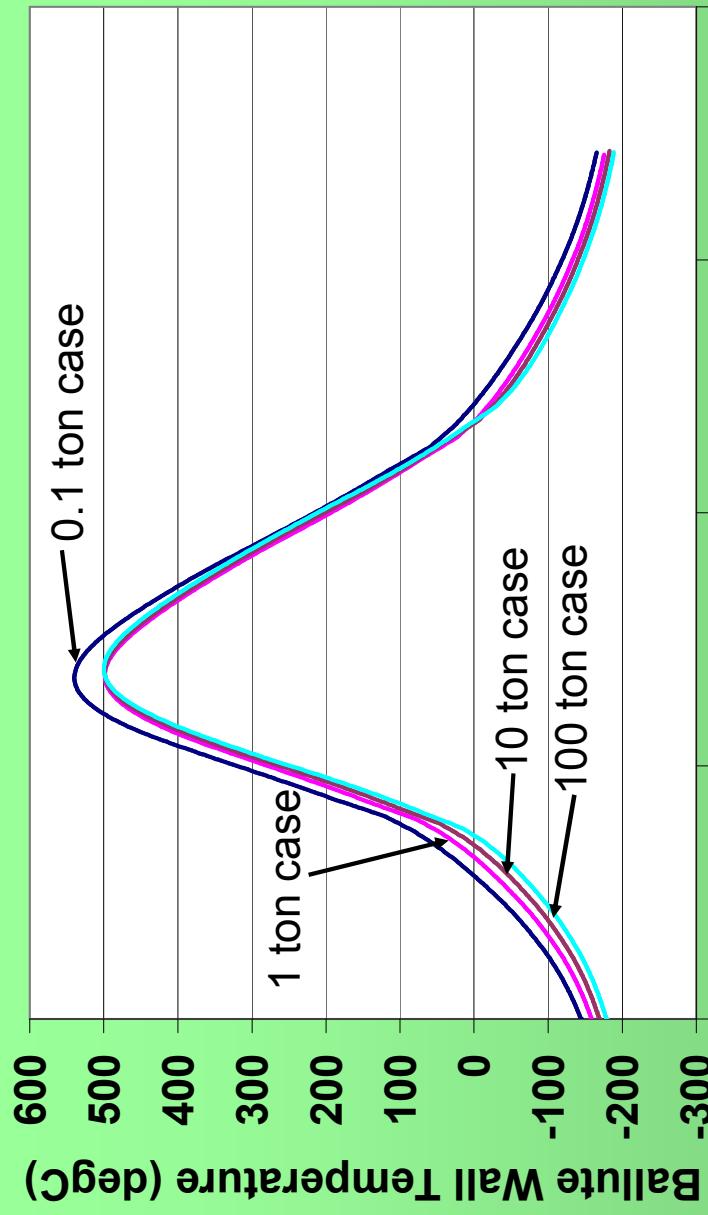
$$Q_s = \frac{C \rho^{0.5} V^3}{\sqrt{R_n}}$$

(based on Sutton-Graves heating approximation)

Larger ballute =  
lower heating rate  
at a given altitude

for Kapton:  $T_{w,\max} = 500^\circ C \rightarrow Q_{s,\max} = 2.01 W/cm^2$

# Stagnation Point Heating Rate



$$T_w^4 = \frac{1}{2\epsilon\sigma} Q_s$$

emissivity ( $\epsilon = 0.5$ )

Stefan-Boltzmann constant  
( $\sigma = 5.67 \times 10^{-8} \text{ kg/s}^3/\text{K}^4$ )

for Kapton:  $T_{w,\max} = 500^\circ\text{C} \rightarrow Q_{s,\max} = 2.01 \text{ W/cm}^2$

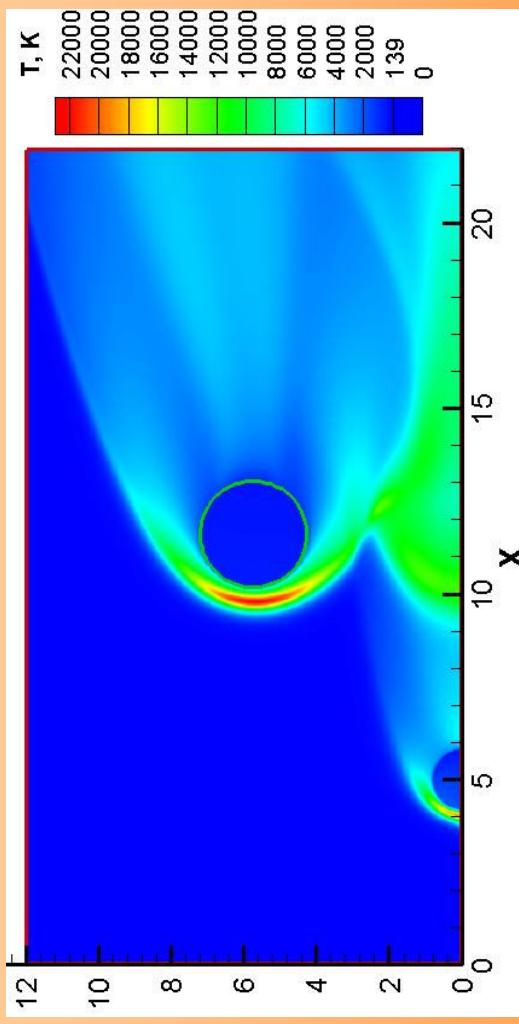
0.1 ton:  $\beta = 0.50$   
1 ton:  $\beta = 0.76$   
10 ton:  $\beta = 1.60$   
100 ton:  $\beta = 3.45$

# Temperature

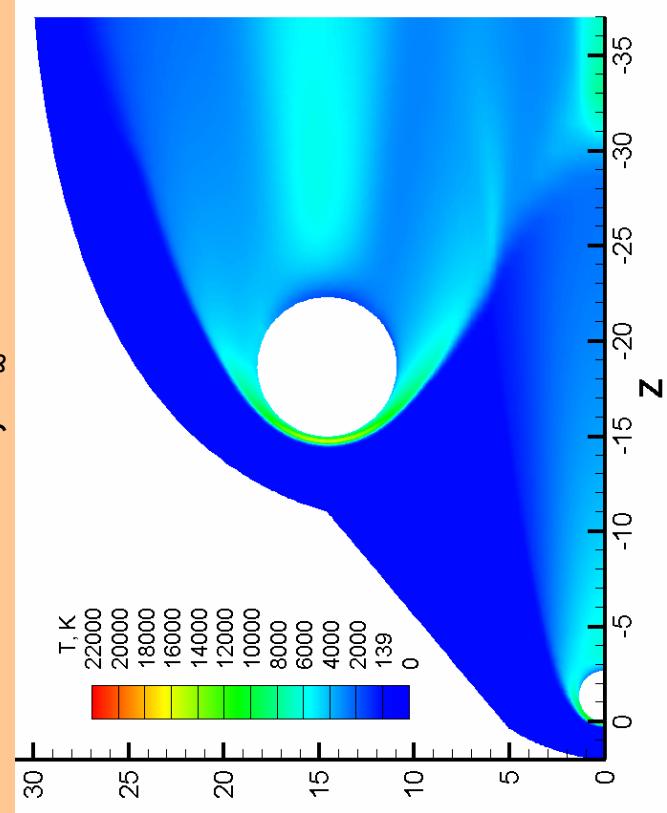


**0.1 ton payload,  $\beta = 0.50$  (DSMC results)**

$Kn = 2.63E-2, V_\infty = 5.38 \text{ km/s}$



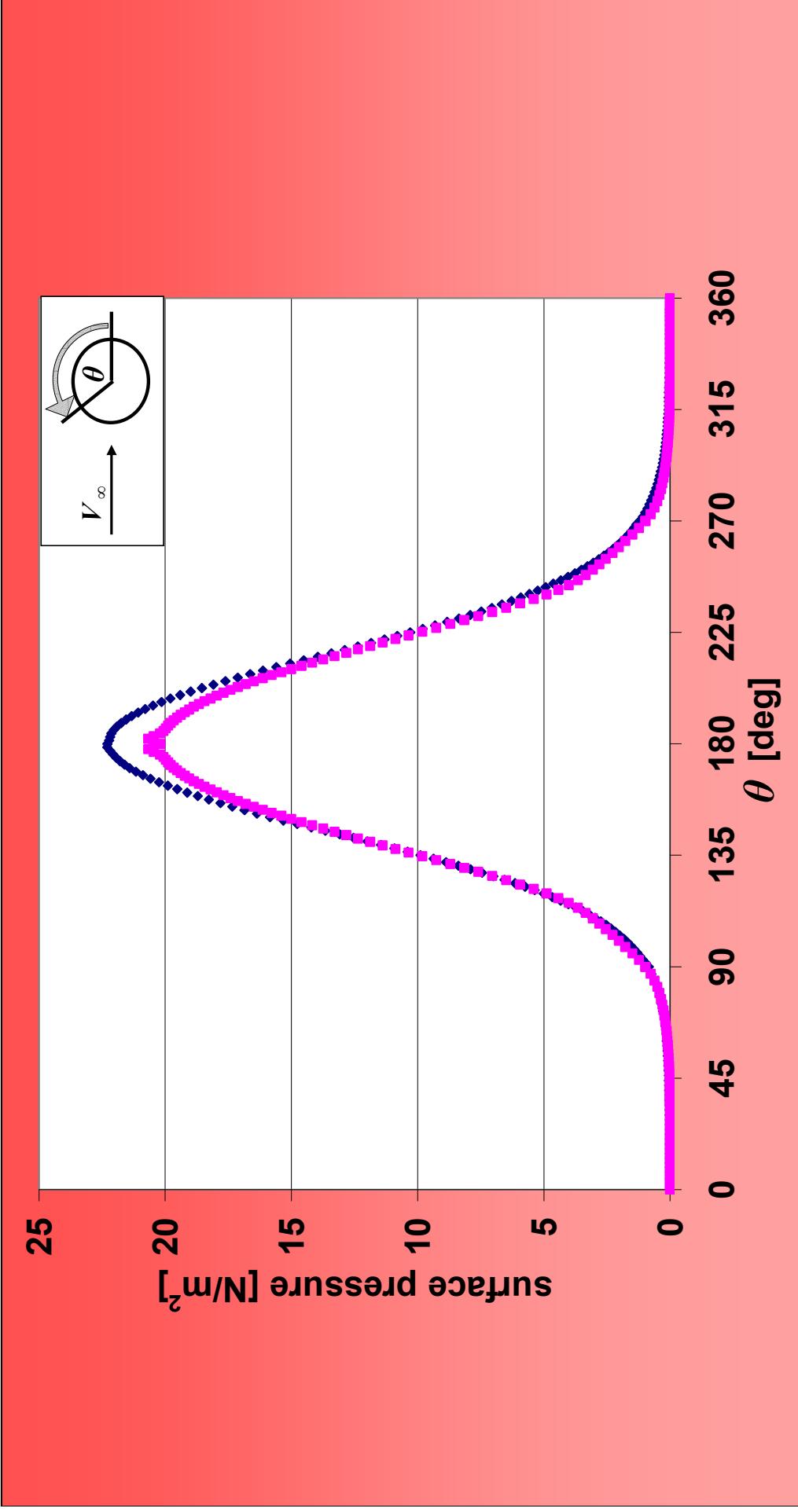
**1 ton payload,  $\beta = 0.76$  (CFD results)**  
 $Kn = 6.20E-3, V_\infty = 5.39 \text{ km/s}$



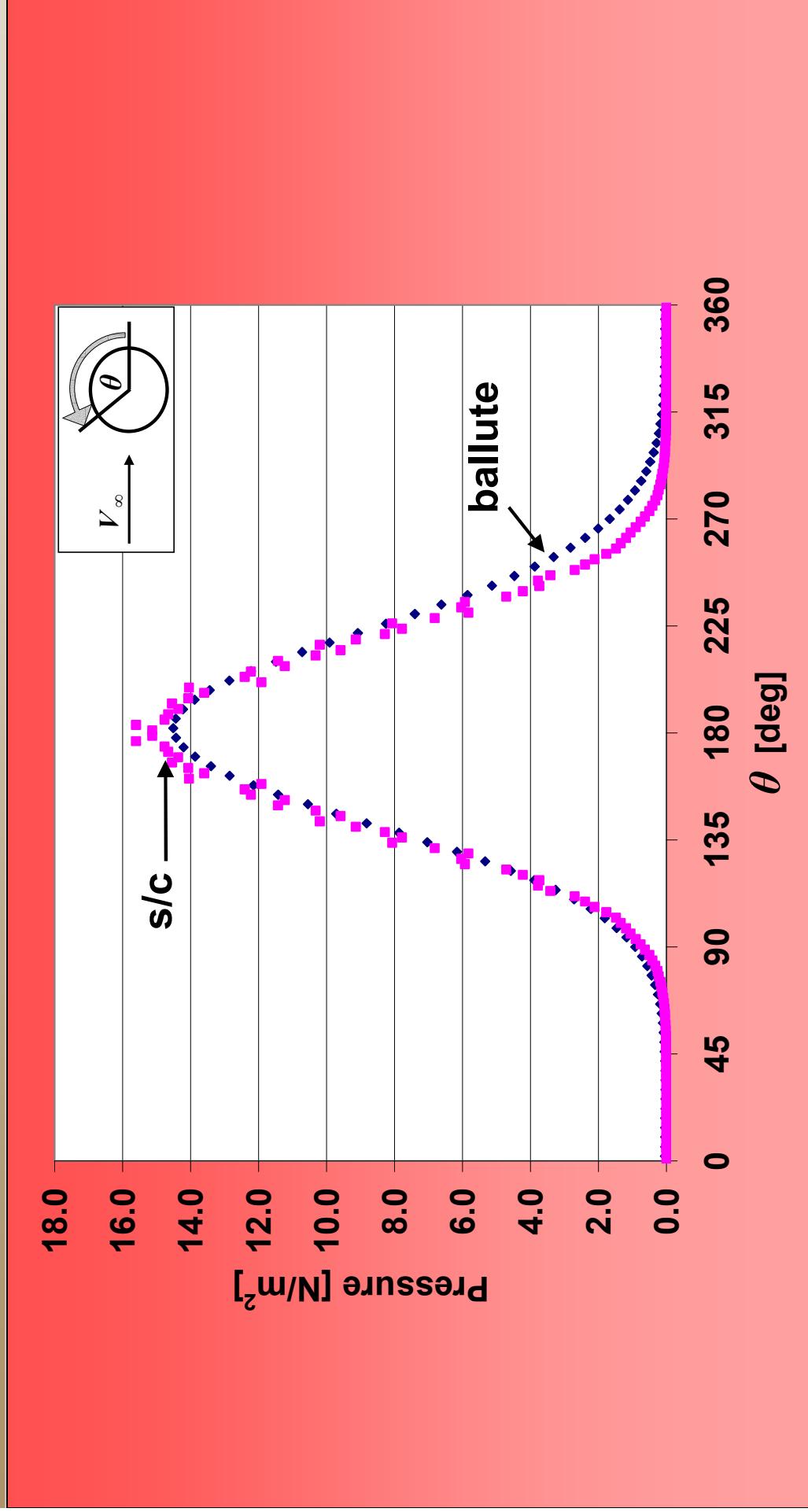
$$T_\infty = 139 \text{ K}$$

**High temperature leads to  $\text{CO}_2$  dissociation, which causes chemical reactions.**

# Surface Pressure (1 ton, CFD)



# Surface Pressure (0.1 ton, DMC)



# Surface Temperature (0.1 ton, DSMC)

